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THE FIFTH VLBA CALIBRATOR SURVEY: VCS5

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ABSTRACT

This paper presents the fifth extension to the Very Long Baseline Array (VLBA) Calibrator Survey (VCS), containing 569 sources not observed previously with very long baseline interferometry. The main goal of this campaign is to observe additional sources supplementing previous survey results to construct a statistically complete sample of extragalactic flat-spectrum radio sources. This VCS extension, based on three 24 hour VLBA observing sessions, detected almost all remaining extragalactic flat-spectrum sources with correlated flux density greater than 200 mJy at 8.6 GHz above declination -30°. It also increases the number of known sources suitable as phase calibrators. Source positions with milliarcsecond accuracy were derived from astrometric analysis of ionosphere free combinations of group delays determined at 2.3 and 8.6 GHz frequency bands. The VCS5 catalogue of source positions, plots of correlated flux density versus projected baseline length, contour plots and fits files of naturally weighted CLEAN images, as well as calibrated visibility function files are available on the Web at http://vlbi.gsfc.nasa.gov/vcs5.

Subject headings: astrometry — catalogues — surveys

1. INTRODUCTION

This work is a continuation of the survey search for bright compact radio sources. Several major applications require an extended list of sources with positions known at a nanoradian level: geodetic observations including space navigation; very long baseline interferometry (VLBI) phase-referencing of weak targets; and differential astrometry. For satisfying needs of these applications, 878 sources were observed under various geodetic and astrometric programs from 1979 thorough 2002, and over 80% of them were detected. Results of these observations were presented in the catalogue ICRF-Ext.2 (Fey et al. 2004) that contains positions of 776 sources. In addition to that, 2952 flat spectrum sources were observed in nineteen 24 hour sessions from 1994 through 2005 under the Very Long Baseline Array (VLBA) Calibrator Survey (VCS) program The positions of 2505 sources were determined from the observations of the VCS project: VCS1 (Beasley et al. 2002), VCS2 (Fomalont et al. 2003), VCS3 (Petrov et al. 2005), and VCS4 (Petrov et al. 2006). Since 364 sources are listed in both the ICRF-Ext.2 and the VCS catalogues, the total number of sources for which positions were determined with VLBI is 2917. Among them, 2468 sources, or 85%, are considered acceptable calibrators: having at least 8 successful observations at both X (central frequency 8.6 GHz) and S (central frequency 2.3 GHz) bands, and the semi-major axis of the error ellipse of their coordinates being less than 25 nrad ($\approx$ 5 mas). When observations under both geodetic programs and VCS are combined, the overall catalogue provides fairly good sky coverage. The probability of finding a calibrator within 4° of any target above -40° is 98.1%.

In this paper we present an extension of the VCS catalogues, called the VCS5 catalogue. It concentrates on the brightest flat-spectrum sources north of declination -30° previously not observed with VLBI under geodetic and astrometric programs.

Since the observations, calibrations, astrometric solutions and imaging are similar to that of VCS1–4, most of the details are described by Beasley et al. (2002) and Petrov et al. (2005). In §2 we discuss scientific objectives for the VCS5 survey. In §3 we describe the strategy for selecting 675 candidate sources observed in three 24 hour VCS5 sessions with the Very Long Baseline array (VLBA) based on analysis of the available multi-frequency non-VLBI continuum radio measurements. The same strategy was successfully applied by us earlier to select one hundred objects with the strongest estimated flux density at 8.6 GHz in the framework of the VCS4 survey. Sixty seven out of these one hundred VCS4 candidates showed X-band correlated flux density greater than 0.2 Jy (Petrov et al. 2006). In §4 we briefly outline the obser-

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vations and data processing. We present the VCS5 catalogue in §5, and summarize our results in §6.

2. SCIENTIFIC OBJECTIVES FOR THE VCS5 SURVEY

A cursory analysis of the sample of 2917 sources with precise positions revealed that it is nearly complete at a 0.5 Jy level, but becomes incomplete at a lower flux density limit. As a result, possible usage of this largest collection of VLBI data for statistical analysis of properties of active galactic nuclei at milliarcsecond scales is limited. The main goal of the current VCS5 project is to observe the remaining bright sources with expected correlated flux densities in the range 200–600 mJy in order to create a statistically complete sample of extragalactic flat-spectrum radio sources with integrated flux density at milliarcsecond scales greater than 200 mJy at X band. This will make results of the VCS survey significantly more useful for astrophysical applications. The uniformity of VCS data reduction as well as the completeness and homogeneity of the source sample will guarantee robust results of further statistical studies. In addition, these observations will provide more *bright* calibrators for phase-referencing observations. For many applications a more distant bright calibrator is preferable to a near-by but weaker calibrator, since more time can be spent on the target.

3. SOURCE SELECTION

Our source selection goal was to find all flat-spectrum radio sources brighter than 0.2 Jy at 8.6 GHz that are missing in the VCS1–4/ICRF-Ext2 catalogs. We define flat radio spectrum as having a spectral index $\alpha > -0.5$ ($S \sim \nu^{\alpha}$). To compile a list of missing objects, we first selected all sources from the NVSS catalog (Condon et al. 1998) with flux density at 1.4 GHz $S > 50$ mJy, declination $\delta > -30°$, a galactic latitude $|b| > 1.^{\circ}5$, and not identified with galactic objects. Since the NVSS catalogue is more than 99% complete for flux density $S > 50$ mJy, it is unlikely that sources with highly inverted spectra and flux density $S > 200$ mJy at 8.6 GHz will be missed.

We then searched the CATS database (Verkhodanov et al. 1997) containing almost all radio catalogs[3] to find flux density measurements at other radio frequencies. These data were supplemented by results of the 1–22 GHz instantaneous broad-band spectra measurements of $\sim$3000 extragalactic flat-spectrum radio sources which we performed at the transit mode 600 m ring radio telescope RATAN-600 of the Russian Academy of Sciences (see, e.g., Kovalev et al. 1999). The collected data were then analyzed semi-automatically, and bad data points, wrong identifications, multiply data points corresponding to different components of the same extended object, etc., were flagged. We found that we could compile a complete sample of sources with total spectrum flatter than $\alpha = -0.5$, and with estimated total flux density of $S > 170$ mJy at 8.6 GHz. In this complete sample were 675 candidates not previously observed in geodetic VLBI mode, and these are the sources selected for VCS5 observations. Figure 1 presents examples of plots of the total flux density spectra collected by the CATS database which we used for source selection.

Our analysis of the multi-frequency catalogs and RATAN observations used for selection indicates that we have found all of the sources with spectral index greater than –0.5 and estimated total flux density at 8.6 GHz $S > 170$ mJy. It is based on the fact that many used catalogs including NVSS (Condon et al. 1998), FIRST (White et al. 1997), 87GB (Gregory & Condon 1991), GB6 (Gregory et al. 1996), CLASS (Myers et al. 2003), JVAS (Patnaik et al. 1992; Browne et al. 1998; Wilkinson et al. 1998), PMN (Wright et al. 1994; Griffith et al. 1995; Wright et al. 1996), and PKScat90 (Wright & Otrupcek 1990), are complete down to 150–250 mJy and below. This should provide us with a sample of the same completeness characteristics. However, it is well known that flat spectrum sources are variable (e.g., Kellermann & Pauliny-Toth 1968); consequently, the variability corrupts at a certain degree our estimations of spectral index and total flux density. The membership of a source in the completeness sample is also changeable and depends on the observation epochs of the various compilation surveys. The quantitative analysis of completeness of the resulting correlated flux density limited sample of the sources from the combined ICRF-Ext.2 and VCS1–5 catalogs will have to take into account the frequency dependent variability properties (e.g., Kovalev et al. 2002) as well as compactness characteristics of flat spectrum sources (e.g., Popov & Kovalev 1999; Kovalev et al. 2005). This is beyond the scope of the present paper and is deferred to another publication. We expect the present sample to be sufficiently complete and robust for most statistical studies of flat-spectrum radio sources.

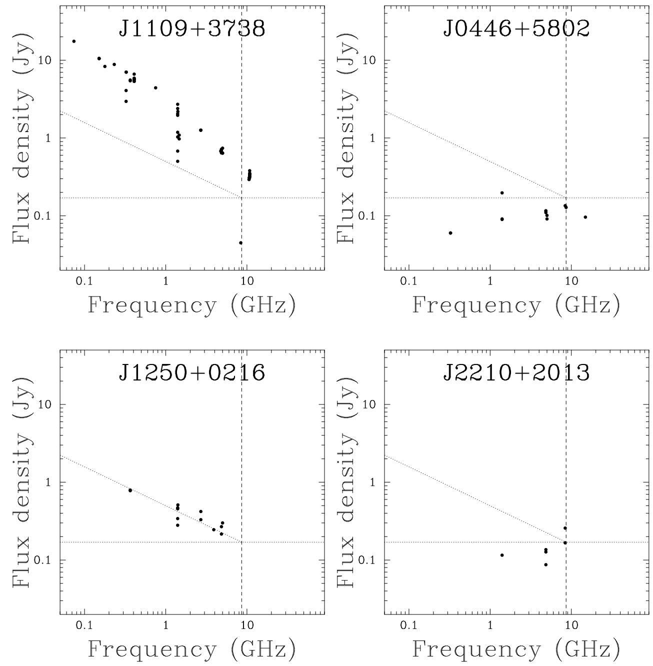

FIG. 1.— Illustration of the candidates selection procedure. The data points were provided by the CATS data base from all available published observational data. J1109+3738 was not selected since its integrated spectral index is lower than −0.5. The dotted falling lines represent $\alpha = -0.5$. J0446+5802 was not selected since its flux density extrapolated to 8.6 GHz was less than 170 mJy. J1250+0216 and J2210+2013 satisfied all the selection criteria mentioned in § 3 and were selected. Their *uv* and image data are presented in Figure 3.

4. OBSERVATIONS AND DATA PROCESSING

The VCS5 observations were carried out in three 24 hour observing sessions with the VLBA on 2005 July 8, July 9, and July 20. Each of the 675 target source was observed in two scans of 120 seconds each. The target sources were observed in a sequence designed to minimize loss of time from antenna slewing. In addition to these objects, 97 strong

[3] http://cats.sao.ru/doc/CATS_list.html

sources were taken from the GSFC astrometric catalogue `2004f_astro`[4]. Observations of 3–4 strong sources from this list were made every 1–1.5 hours. These observations were scheduled in such a way that at each VLBA station at least one of these sources was observed at an elevation angle less than 20°, and at least one at an elevation angle greater than 50°. The purpose of these observations was to provide calibration for mis-modeled atmospheric path delays and to tie the VCS5 source positions to the ICRF catalogue (Ma et al. 1998). The list of troposphere calibrators[5] was selected from the sources which, according to the 2 cm VLBA survey results (Kovalev et al. 2005), showed the greatest compactness index, i.e. the ratio of the correlated flux density measured at long VLBA spacings to the flux density integrated over the VLBA image. In total, 772 targets and calibrators were observed. The antennas were on-source about 65% of the time.

Similar to the previous VLBA Calibrator Survey observing campaigns (e.g., Petrov et al. 2006), we used the VLBA dual-frequency geodetic mode, observing simultaneously at S and X band. Each band was separated into four 8 MHz channels (IFs) which spanned 140 MHz around 2.3 GHz and 490 MHz around 8.6 GHz, in order to provide precise measurements of group delays for astrometric processing. Since the a priori coordinates of candidates were expected to have errors of up to 30″, the data were correlated with an accumulation period of 1 second in 64 spectral channels in order to provide an extra-wide window for fringe search.

Processing of the VLBA correlator output was done in three steps. In the first step the data were calibrated using the Astronomical Image Processing System (AIPS) (Greisen 2003). In the second step data were imported to the Caltech DIFMAP package (Shepherd 1997), *uv* data flagged, and maps were produced using an automated procedure of hybrid imaging developed by Greg Taylor (Pearson et al. 1994) which we adopted for our needs. We were able to reach the VLBA image thermal noise level for most of our CLEAN images (Wrobel & Ulvestad 2006). Errors of our estimates of correlated flux density values for sources stronger than ∼100 mJy are determined mainly by the accuracy of amplitude calibration, which for the VLBA, according to Wrobel & Ulvestad (2006), is at the level of 5% at 1–10 GHz. An additional error is introduced by the fact that our frequency channels are widely spread over receiver bands while the VLBA S- and X-band gain curve parameters are measured around 2275 and 8425 MHz respectively (Wrobel & Ulvestad 2006), and the noise diode spectrum is not ideally flat. However, this should not add more than a few percent to the total resulting error. Our error estimate was confirmed by comparison of the flux densities integrated over the VLBA images with the single-dish flux densities which we measured with RATAN–600 in June and August 2005 for slowly varying sources without extended structure. The methods of single-dish observations and data processing can be found in Kovalev et al. (1999). In the third step, the data were imported to the Calc/Solve program, group delays ambiguities were resolved, outliers eliminated, and coordinates of new sources were adjusted using ionosphere-free combinations of X band and S band group delay observables of the 3 VCS5 sessions, 19 VCS1–4 experiments and 3976 24-hour International VLBI Service for astrometry and geodesy (IVS) experiments[6] in a single least square solution. Positions of 3486 sources were estimated including all detected VCS5 sources: 590 targets and 97 tropospheric calibrators. Boundary conditions were imposed requiring zero net-rotation of position adjustments of the 212 sources listed as defining sources in the ICRF catalogue with respect to their coordinates from that catalogue.

In a separate solution, coordinates of the 97 well known tropospheric calibrators were estimated from the VCS5 observing sessions only. Comparison of these estimates with coordinates derived from the 3976 IVS geodetic/astrometric sessions provided us a measure of the accuracy of the coordinates from the VCS5 observing campaign. The differences in coordinate estimates were used for computation of parameters a and $b(\delta)$ of an error inflation model in the form $\sqrt{(a\sigma)^2+b(\delta)^2}$, where σ is an uncertainty derived from the fringe amplitude signal to noise ratio using the error propagation law and δ is declination. More details about the analysis and imaging procedures can be found in Beasley et al. (2002) and Petrov et al. (2005). The histogram of source position errors is presented in Figure 2.

In total, 590 out of 675 sources were detected and yielded at least two good points for position determination. This 87% detection rate confirms the validity of the applied candidate selection procedure (§3). However, not all of these 590 sources are suitable as phase reference calibrators or as targets for geodetic observations. Following Petrov et al. (2005) we consider a source suitable as a calibrator if 1) the number of good X/S pairs of observations is 8 or greater in order to rule out the possibility of a group delay ambiguity resolution error; and 2) the position error before re-weighting is less than 5 mas following the strategy adopted in processing VCS observations. Only 433 sources satisfy this calibrator criteria. Other detected sources are somewhat resolved and/or below the detection limit of these observations of 60 mJy. Some of these may become suitable phase calibrators for future experiments with higher data rates and more sensitivity than the

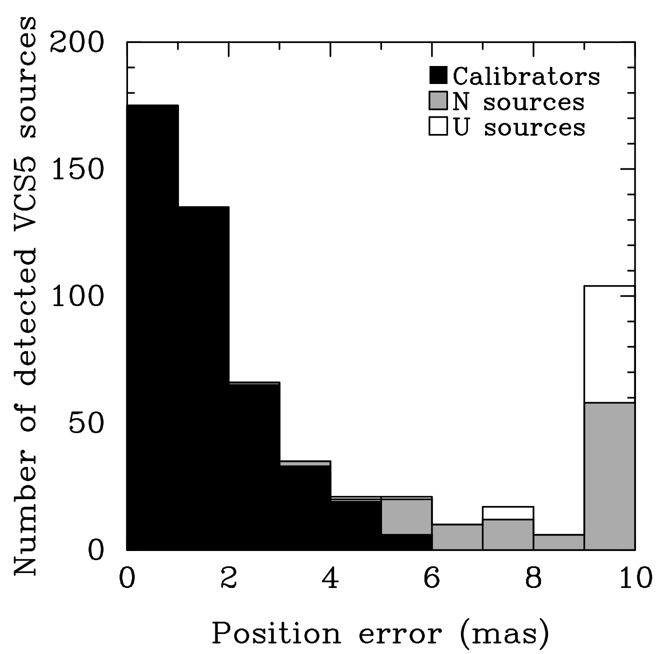

FIG. 2.— Histogram of semi-major error ellipse of position errors. The last bin shows errors exceeding 9 mas. See explanation of different assigned source classes in § 4,5.

[4] http://vlbi.gsfc.nasa.gov/solutions/astro
[5] http://vlbi.gsfc.nasa.gov/vcs/tropo_cal.html
[6] http://vlbi.gsfc.nasa.gov/solutions/2005c

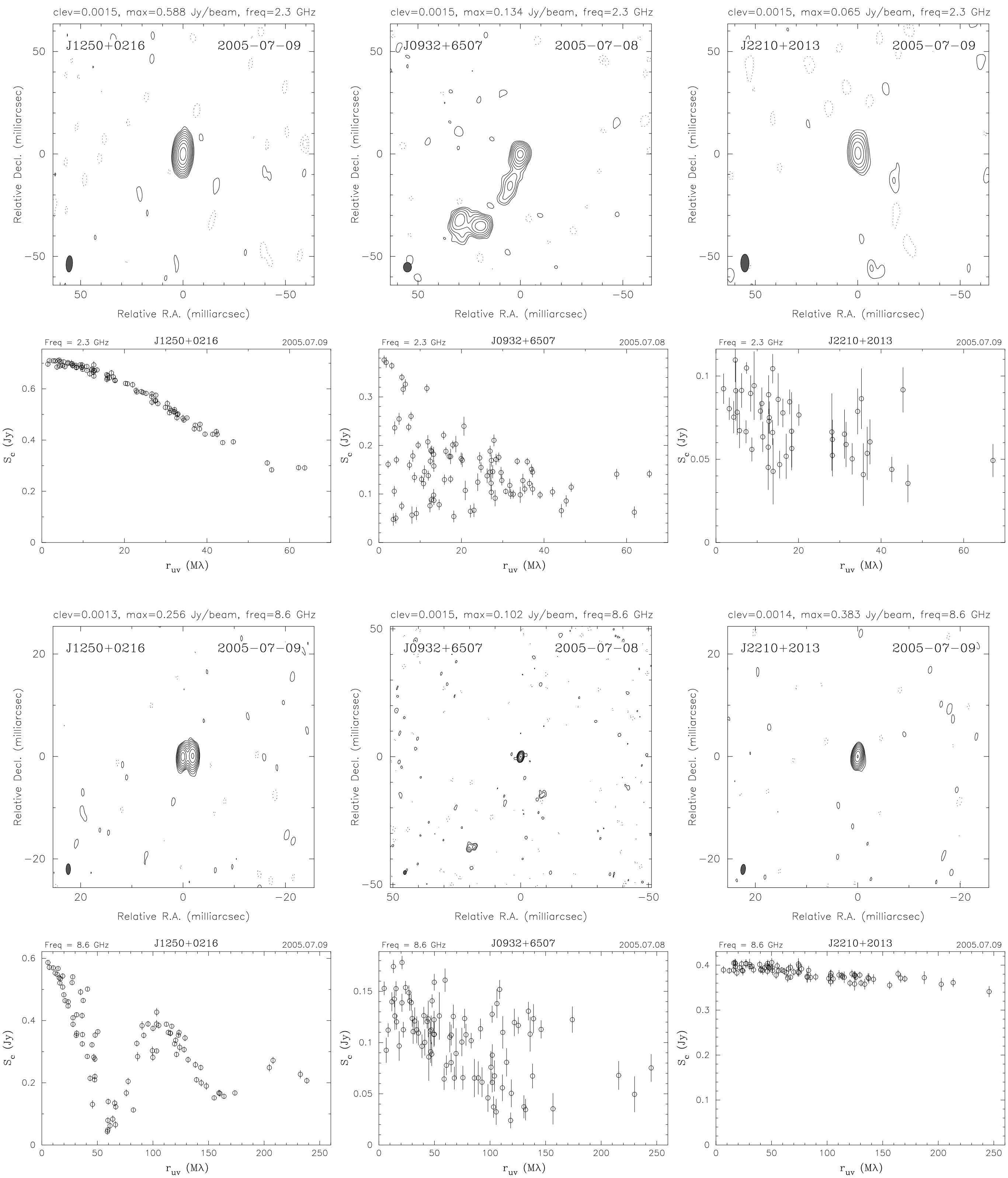

FIG. 3.— From top to bottom. *Row 1:* Naturally weighted CLEAN images at S-band (2.3 GHz). The lowest contour levels (2 steps) on images are plotted at "clev" levels (Jy/beam), the peak brightness — "max" values (Jy/beam). The dashed contours indicate negative flux. The beam is shown in the bottom left corner of the images. *Row 2:* Dependence of the correlated flux density at S-band versus projected spacings. Each point represents a coherent average over one 2 min observation on an individual interferometer baseline. The error bars represent only the statistical errors. *Row 3:* Naturally weighted CLEAN images at X-band (8.6 GHz). *Row 4:* Dependence of the correlated flux density at X-band versus projected spacings.

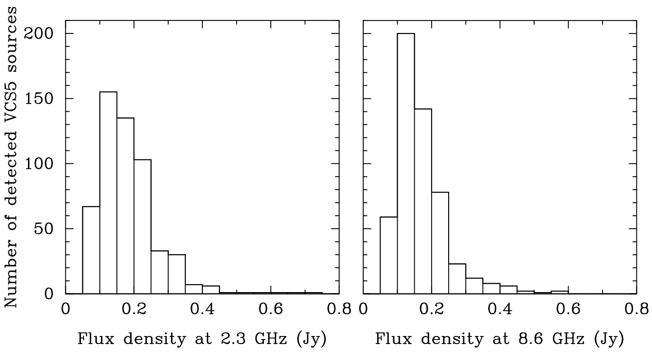

FIG. 4.— Distributions of flux density integrated over VLBA image for all detected VCS5 sources (columns 10 and 12 of the Table 1).

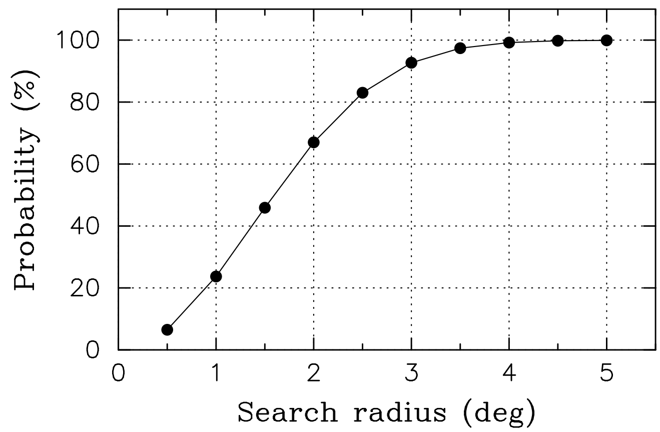

FIG. 5.— The probability (filled circles) of finding a calibrator in any given direction within a circle of a given radius, north of declination −30°. All sources from 3976 IVS geodetic/astrometric sessions and 22 VCS1–5 VLBA sessions which are classified as calibrators are taken into account.

VCS surveys. Among the 157 non-calibrators, 104 have reliable position determinations and 53 unreliable. It should be noted that, due to an omission, the list of target sources contained 21 objects previously observed and detected in the VCS4 campaign.

5. THE VCS5 CATALOGUE

The VCS5 catalogue is listed in Table 1. The first column gives source class: "C" if the source can be used as a calibrator, "N" if it cannot but determined positions are reliable, "U"—non-calibrator, unreliable positions. The second and third columns give IVS source name (B1950 notation), and IAU name (J2000 notation). The fourth and fifth columns give source coordinates at the J2000.0 epoch. Columns /6/ and /7/ give inflated source position uncertainties in right ascension (without $\cos\delta$ factor) and declination in mas, and column /8/ gives the correlation coefficient between the errors in right ascension and declination. The number of group delays used for position determination is listed in column /9/. Columns /10/ and /12/ give the estimate of the flux density integrated over the entire map in Janskies at X and S band respectively. This estimate is computed as a sum of all CLEAN components if a CLEAN image was produced. If we did not have enough detections of the visibility function to produce a reliable image, the integrated flux density is estimated as the median of the correlated flux density measured at projected spacings less than 25 and 7 Mλ for X and S bands respectively. The integrated flux density means the total flux density with spatial frequencies less than 4 Mλ at X band and 1 Mλ at S band filtered out, or in other words, the flux density from all components within a region about or less than 50 mas at X band and 200 mas at S band. Columns /11/ and /13/ give the flux density of unresolved components estimated as the median of correlated flux density values measured at projected spacings greater than 170 Mλ for X band and greater than 45 Mλ for S band. For some sources no estimates of the integrated and/or unresolved flux density are presented, because either no data were collected at the baselines used in the calculations, or these data were unreliable. Column /14/ gives the data type used for position estimation: X/S stands for ionosphere-free linear combination of X and S wide-band group delays; X stands for X band only group delays; and S stands for S band only group delays. Some sources which yielded less than 8 pairs of X and S band group delay observables had 2 or more observations at X and/or S band observations. For these sources either X-band or S-band only estimates of coordinates are listed in the VCS5 catalogue. Column /15/ defines the catalogue name.

In addition to this table, the html version of the catalogue is posted on the Web[7]. For each source it has 8 links: to a pair of postscript maps of the source at X and S-band; to a pair of plots of correlated flux density as a function of baseline length projected to the source plane; to a pair of fits files of CLEAN components of naturally weighted source images; and to a pair of fits files with calibrated *uv* data. This dataset is also accessible from the NRAO archive[8] which links the files to the Virtual Observatory. The positions and the plots are also accessible from the updated NRAO VLBA Calibrator Search web-page[9].

Figure 3 presents examples of naturally weighted contour CLEAN images as well as estimates of the correlated flux density versus projected spacings for three sources: the strongest VCS5 source at X-band, J1250+0216, with two bright components resolved at X- and not resolved at S-band; a steep spectrum source with extended structure, J0932+6507; and the source with the most inverted spectrum and very compact structure at the milliarcsecond scale, J2210+2013.

Figure 4 presents histograms of the 2.3 and 8.6 GHz integrated flux density for 590 detected VCS5 sources, 132 out of which have integrated flux density $S \geq 200$ mJy at 8.6 GHz. Their addition to the previously observed sources will form the statistically complete sample north of declination −30°. It is interesting to note that many of the discovered VCS5 sources have inverted radio spectra. The 50 mJy cutoff for the original selection of sources from the NVSS catalogue allowed us to add inverted spectrum objects in the list of candidates. A few tens of new compact VCS5 objects with high flux density at VLBA baselines will be useful for geodetic applications.

The sky calibrator density for different radii of a search circle for declination $\delta > -30°$ is presented in Figure 5. As discussed in Petrov et al. (2006), the addition of these sources to the VLBA Calibrator list did not affect significantly the density for the search radius of 4°, but increases it for smaller search circles, e.g., the probability of finding a calibrator within 2.°5 is now 83%. This is beneficial for many applications requiring bright compact calibrator within 2-3 degrees

[7] http://vlbi.gsfc.nasa.gov/vcs5
[8] http://archive.nrao.edu
[9] http://www.vlba.nrao.edu/astro/calib

TABLE 1
The VCS5 catalogue

Class	Source name: IVS	Source name: IAU	J2000.0 Coordinates: Right ascension	J2000.0 Coordinates: Declination	Errors (mas): $\Delta\alpha$	Errors (mas): $\Delta\delta$	Corr	# Obs	Correlated flux density (Jy) 8.6 GHz: Total	8.6 GHz: Unres	2.3 GHz: Total	2.3 GHz: Unres	Band	Cat
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
C	0008+006	J0011+0057	00 11 30.403309	+00 57 51.87984	1.02	2.00	0.114	25	0.09	0.07	···	···	X	VCS5
C	0009+467	J0012+4704	00 12 29.302900	+47 04 34.73946	0.77	1.08	–0.371	35	0.13	0.12	0.10	<0.06	X/S	VCS5
N	0013–240	J0016–2343	00 16 05.738818	–23 43 52.18956	30.58	16.85	–0.808	17	···	···	0.15	0.08	S	VCS5
C	0015–054	J0017–0512	00 17 35.817204	–05 12 41.76727	0.46	0.92	–0.278	54	0.20	0.12	0.14	0.09	X/S	VCS5
C	0015–280	J0017–2748	00 17 59.006128	–27 48 21.57153	1.75	3.51	0.712	32	0.24	0.16	0.20	0.06	X/S	VCS5
C	0034+078	J0037+0808	00 37 32.197173	+08 08 13.05750	0.38	0.50	–0.225	76	0.25	0.14	0.19	0.10	X/S	VCS5
C	0035–037	J0038–0329	00 38 20.794340	–03 29 58.96178	0.32	0.63	–0.347	77	0.20	0.16	0.31	0.21	X/S	VCS5
N	0036–191	J0039–1854	00 39 16.924431	–18 54 05.61863	4.97	9.83	0.749	8	0.12	···	0.18	0.10	X/S	VCS5
C	0037+011	J0040+0125	00 40 13.525489	+01 25 46.35014	0.99	1.94	–0.124	29	0.11	<0.06	<0.06	···	X	VCS5
C	0041+677	J0044+6803	00 44 50.759589	+68 03 02.68607	0.91	0.58	–0.130	59	0.28	0.22	0.14	<0.06	X/S	VCS5

NOTE. — Table 1 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and contents. Assigned source class in (1) is 'C' for calibrator, 'N' for non-calibrator with reliable coordinates, 'U' for non-calibrator with unreliable coordinates; see § 4,5 for details. Units of right ascension are hours, minutes and seconds; units of declination are degrees, minutes and seconds.

of a target.

6. SUMMARY

The VCS5 Survey has made a significant step towards constructing a homogeneous statistically complete sample of flat-spectrum compact extragalactic radio sources north of declination $-30°$ with integrated VLBA flux density greater than about 200 mJy at 8 GHz. The VCS5 Survey has added 569 new sources, not previously observed with VLBI. Among them, 433 sources are suitable as phase referencing calibrators and as target sources for geodetic applications. After processing the VCS5 experiments, the total number of sources with positions known at the nanoradian level is 3486, and the number of VLBI calibrators has grown from 2472 to 2905. This pool of calibrators was formed from analysis of 22 VLBI Calibrator Survey and 3976 24-hour four hour IVS astrometry and geodesy observing sessions.

In the present paper we do not yet provide quantitative estimates of completeness of our list of compact flat-spectrum sources. In order to get these estimates we are going to (i) complete the homogeneous imaging of all of 3486 sources and get estimates of their integrated flux densities at milliarcsecond scales at the X and S bands, (ii) complete processing *instantaneous* single-dish multi-frequency, multi-epoch flux density measurements with RATAN–600 for this sample; (iii) observe a total flux density limited sample of all sources regardless of their spectral index over a relatively large portion of the sky complemented with simultaneous multi-frequency single-dish measurements. The latter will allow us to assess whether conclusions drawn from the VLBI flat-spectrum source samples can be extended to the whole population of extragalactic objects regardless their continuum spectrum characteristics.

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